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A review of the state of biomass energy technologies in Zimbabwe

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ABSTRACT

Biomass supplies about 66% of total energy consumption in Zimbabwe. In recent times there has been an increasing interest in the country to increase the utilization of biomass resources for energy purposes. The major biomass materials found in Zimbabwe are fuelwood, crop and forestry residues, animal dung, energy crops, municipality and industrial wastes. Biomass energy conversion technologies include anaerobic digestion, pyrolysis, gasification, transesterification, fermentation and combustion. The premise of this paper is that as a component of a renewable energy mix, biomass should play an important role in sustainable energy systems in Zimbabwe. With an estimated total energy value of 409 pJ, biomass is a huge energy resource for the country and must be optimally exploited. However, traditional utilization of solid biomass materials as a primary source of energy continues to be prevalent in Zimbabwe today. The trend should be to move from traditional biomass energy to improved and modern biomass energy technologies. This is evidenced by numerous projects that have been undertaken in pursuit of this endeavor. The aim of this paper is to review the state of biomass energy technologies in Zimbabwe with a view to provide aggregated information that will inform research, development and policies related to biomass energy.

Contents

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1. Introduction

Biomass energy forms the bulk of final energy supply in sub-Saharan Africa (SSA). Energy consumption in Zimbabwe is about 280 pJ/year^{-1} [1]. Biomass supplies 66% of this energy. Over 76% of the country's population (about 10 million people) relies on biomass for energy [2,3]. Biofuels supply about 85% of domestic energy requirement in the country [4]. Energy consumption in Zimbabwe has grown at a rate of about 3.5% per annum [1]. Some estimates indicate that biomass use for energy purposes in countries like Zimbabwe will increase through to 2020 at the same rate as population growth rates [5]. The energy mix in the country also includes coal, petroleum, solar and hydropower. The structure of energy supply in the country is shown in Fig. 1.

It is now generally accepted that biomass has the potential to become one of the major primary energy sources during this century, and modernized bioenergy systems are important for the development of sustainable energy systems [7,8]. The bulk of bioenergy used in SSA is traditional biomass energy [9]. Traditional biomass energy refers to the direct combustion of various forms of solid biomass materials [10]. There is a need to shift towards improved traditional biomass and modern biomass energy technologies [10]. The term improved traditional biomass energy refers to improved and more efficient technologies for direct combustion of biomass [10]. Modern biomass energy use refers to the conversion of biomass energy to advanced fuels, mainly liquid and gaseous fuels [11].

The drawbacks of traditional biomass use for energy are well documented [12–14]. Similarly, advances in biomass energy technologies are also well documented. Clean, convenient and modern energy carriers can be derived from biomass. Conversion routes to produce heat, electricity and fuels from biomass are well established and supported by continuous research and development [15,16]. The conversion technologies are mainly physical, thermochemical and biochemical processes. These include combustion, gasification, pyrolysis, liquefaction, anaerobic digestion, fermentation and trans-esterification.

A number of modern biomass energy technologies are now at different stages of research, development, demonstration and commercialization [15,17]. Gasification technology is more than a century old. Anaerobic digestion is a mature technology. Electricity generation based on biomass combustion employing boiler-steam turbine systems is well established [17]. On the other hand, co-firing of biomass with coal has been demonstrated [18,19] and biomass based cogeneration technology is also well established in agro-industries. Production of biodiesel and bioethanol are some of the most impressive biomass energy technologies in existence today.

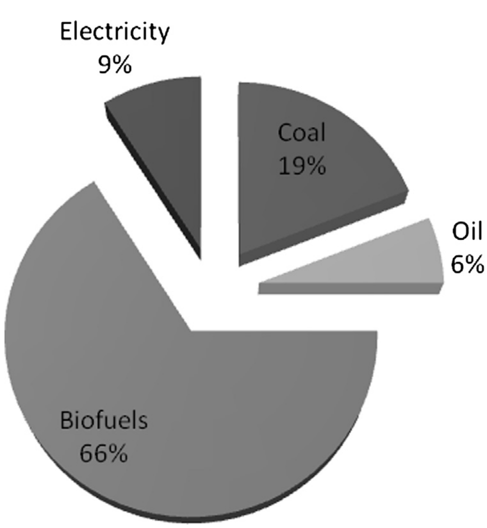

Fig. 1. Energy supply in Zimbabwe for 2009.

The premise of this paper is that as a component of a renewable energy mix, biomass should play an important role in sustainable energy systems in Zimbabwe. With an estimated total energy value of 409 pJ, biomass is a huge energy resource for the country and must be optimally exploited. The aim of this paper is to review the state of biomass energy technologies in Zimbabwe with a view to provide aggregated information that will inform research, development and bioenergy policies.

2. Biomass energy resources and their potential for energy production in Zimbabwe

Biomass refers to the solid carbonaceous material derived from plants and animals [20,21]. Biomass resources in Zimbabwe include agricultural, municipal and industrial wastes. Total biomass energy theoretically available in Zimbabwe has been estimated at 409 pJ [20]. Use of biomass materials as sources of energy has been extensively studied in Zimbabwe [20,22,23]. The most common biomass materials used in the country are fuelwood, wood residues, forestry residues, energy crops, crop residues, animal wastes and municipality wastes. The energy potential of these materials is shown in Table 1.

2.1. Standing biomass and fuelwood

Total annual terrestrial above-ground plant woody biomass production in Zimbabwe was estimated to be equivalent to 713 pJ [20]. This is made up of standing biomass resources such as forest plantations which account for 0.4% of land, natural forests 0.3%, woodlands 53.2%, bushland 12.7%, wooded grassland 3.1%, grassland 1.8%, and cultivated land 37.5% [24]. Fuelwood supplies about 98% of the biomass energy consumed in Zimbabwe [3] and accounts for 85% of household energy consumed in the country [24]. About 6 million tones of wood are consumed annually, mainly by rural and urban low-income households. This represents a total of about 2000 ktOe.

2.2. Crop residues, forestry materials and animal wastes

The major crops grown in Zimbabwe can be divided into three categories, which are grain crops (maize, sorghum, and wheat); cash crops (cotton, groundnuts, soybeans, sunflowers, sugarcane, and tea) and fruit crops. These crops give rise to various types of crop residues. Crop residues constitute a large part of the biomass available in the country. These residues arise from harvesting and processing activities. Sugarcane provides the largest quantities of

Table 1
Biomass energy resources in Zimbabwe and their energy potential.

Type of biomass	Quantities (thousand t year^{-1})	Energy potential (ktoe)[a]	Reference for biomass quantity
Fuelwood	5654	2019	[31]
Charcoal	14	10	[31]
Animal waste	4481	1872	[20]
Crop residues	10,862	2929	[20]
Sawmill waste	750	232	[6]
Forestry waste	2300	833	[20]

[a] Kiloton of oil equivalent.

crop residues on a weight basis, making up 55% of the total crop residues produced in the country [22].

There is a vast timber industry in Zimbabwe along the Eastern Highlands. The plantations occupy 0.02% of the total land area of Zimbabwe comprising 810 km^2 of pine, 240 km^2 of eucalyptus and 130 km^2 of wattle [25]. Forestry and sawmill residues are useful energy carriers. The energy potential of the 750 kt of sawmill residues produced annually is estimated at 232 ktOe [6]. Similarly, the energy potential of forestry residues is 833 ktoe [20]. These values are equivalent to 9.8 and 34.5 pJ for sawmill and forestry residues, respectively.

Zimbabwe has a substantial population of livestock. The main species are cattle, pigs, sheep and goats. The country produces about 4 million tones of animal waste each year. The livestock are distributed across both rural and commercial agriculture sectors. Animal manure is a suitable substrate for biofuels. Estimates of quantities of manure and the associated energy potential are shown in Table 1.

2.3. Municipality solid waste (MSW) and sewage sludge

Zimbabwe has 19 major towns with a combined population of 3,392,144 people [26]. Per capita MSW generation has been estimated at about 0.5 kg day^{-1}. This indicates a potential to produce about 1696 t of MSW per day. The total MSW produced per year in these towns is 552,975 t. Studies have shown that municipalities collect about 82% of the waste generated daily [27]. This reduces the total to 500,415 t of MSW collected annually. The content of putrescibles in MSW in Zimbabwe has been reported to range from 10% to 45% [27]. Assuming that all the 500,415 t of MSW produced per year are landfilled, and using a landfill gas yield of 62 $m^3\ t^{-1}$ of MSW [28], a total of 31,025,730 m^3 of biogas can be generated in landfills. This is equivalent to about 1,706,415 m^3 of methane.

Sewage sludge is a resource that is widely available and has potential to generate energy for the country. The four major towns in Zimbabwe (Harare, Mutare, Masvingo and Bulawayo) generate 300,000; 30,000; 16,800 and 35,000 t day^{-1} of sewage, respectively [29]. Biogas yields from anaerobic digestion of sewage sludge can vary from 250 to 350 $m^3\ t^{-1}$ of organic solids [30]. Thus, there is potential to produce substantial quantities of biogas from sewage sludge in the country.

2.4. Energy crops

The Zimbabwean government has shown interest in *Jatropha curcas* as the appropriate non-food energy crop. The popularity of *Jatropha* is derived from the number of potential benefits that can be expected from its cultivation, ranging from the multiple uses of its oil, ability to reclaim degraded lands [32] to promoting rural entrepreneurship [33].

From 2005 production of *Jatropha* gathered momentum in Zimbabwe. The target was to reach 10% blending of petro-diesel with biodiesel by 2010 [34]. This was not achieved by 2013. The plan was to grow 1220 km^2 of *Jatropha* which would supply about 365,000 t of seed. This would provide about 110 dam^3 of biodiesel required to achieve a blending level of 10% with petro–diesel. Statistics in 2012 indicated that about 60 km^2 of land had been put under *Jatropha* in Zimbabwe. However, as discussed in Section 4.8, this stockfeed production program was facing problems.

3. Biomass conversion technologies

Biomass must be converted to biofuels from which bioenergy is derived. There are at least five different forms of biofuels which are in use today [35]. These are bioethanol, biodiesel, biogas, biomethanol and biohydrogen. Only the first three are produced in Africa [35].

Several processes have been widely applied to convert biomass into biofuels [36]. Biomass conversion technologies can be categorized as traditional, improved or modern [10]. Traditional technologies rely mainly on inefficient systems such as open fires for cooking and space heating. Improved technologies aim to increase efficiency. An example is improved cooking stoves. Modern technologies comprise physical, thermo-chemical and biochemical processes [21,37]. Further details on these technologies are given in Table 2.

4. Domestic and industrial use of biomass conversion technologies in Zimbabwe

Table 2 shows a whole gamut of technologies that are available to convert biomass into various energy carriers. Most of these technologies are mature and have wide commercial applications

Table 2
Conversion technologies for transforming biomass into energy [21,35,38].

Technology	Sub-categories of technology	Products	State of technology	Extent of use in Zimbabwe
Direct combustion	– Direct combustion to produce heat – Direct combustion to produce steam – Co-firing – Co-generation	– heat – Radiant heat, hot gases – Electrical energy – Heat (steam), electrical energy	– mature – mature – mature – mature	– dominant use – industrial use – none – industrial use
Pyrolysis	– Fast pyrolysis – Slow pyrolysis (carbonization)	– Bio-oil, gas, solid char – Char, tar, gas	– Development – Mature	– None – limited use
Gasification	– Steam gasification	– Gas, char, liquid residue	– mature	– limited use
Densification	– Briquetting – Pelletting	– Briquettes – Pellets	– mature – mature	– limited use – none
Liquefaction	– hydro-thermal	– Bio-oil	– mature	– none
Biochemical	– Fermentation – Biomethanation – Trans-esterification	– Alcohol – Biogas – Biodiesel	– mature – mature – mature, research	– industrial use – limited use – industrial use

on a global scale. It is important to note that research, development, demonstration and commercialization are continuous processes in the biofuels industry. The state of utilization of these technologies to produce energy in Zimbabwe will be reviewed for the categories shown in Table 2.

4.1. Direct combustion for cooking and space heating

In Zimbabwe energy required for cooking constitutes the bulk of the total domestic energy consumption. Fuelwood is the most important fuel for cooking and space heating in low-income households, both in urban and rural areas. Crop residues and animal dung are also used for cooking and space heating. The open fire method is the traditional method of cooking and space heating [20,29]. Hosier [39] reported that high open grate stoves are widely used in rural Zimbabwe. What is worth noting is that the open fire method, despite known weaknesses, continues to be used up to this day as a major energy conversion technology. Open fires are only about 10% efficient [40] with a range of 5% to 10%. If all the fuelwood available in the country (2019 ktOe) was burnt in open fires, only 201 ktoe would be effectively useful. In some cases where the fire is well managed and shielded, efficiencies have been improved to 12–17% [20]. This is still an inefficient way of utilizing of a finite resource [41].

In addition to low efficiencies, the traditional open fire method has a number of other drawbacks. The indoor air pollution caused by burning unprocessed fuelwood has been linked to respiratory diseases in many developing countries [12,42]. Indoor open fires have negative impacts on women and children who are the most vulnerable groups in terms of exposure to indoor air pollution impacts [10]. In addition, the low efficiencies of open fires have been linked to deforestation in Zimbabwe [29], although there is no consensus in literature on the link between fuelwood use and deforestation.

The realization of the need to improve efficiencies of open fires led to a global initiative to introduce improved cooking stoves (ICS) in 1981 [43]. Efficiencies can be improved to above 40% with ICS [40]. In Zimbabwe, the Department of Energy initiated the ICS program in 1982. An ICS stove known locally as the *Chingwa* stove was developed and disseminated throughout the country. This stove has 3 pot holes, a hot plate for multi-cooking, brick body and a flue chimney and an oven for baking. At the same time, another prototype made of metal was developed and tested. This is known as the *Tsotso* stove.

The ICS program led to the installation of 114,000 stoves throughout the 57 districts of the country [29]. This translates to about 5.7% of the rural households. However, data by 2001 began to show that these stoves were no longer in use and people had resorted to the traditional open fire system [29]. By 2012, there was little evidence on the use of ICS. Reasons that have been given for the failure of the ICS program include lack of social acceptance; financial barriers; technology that failed to meet people's requirements; and lack of appreciation of benefits from using such stoves [29]. By comparison, it can be noted that the ICS program was more successful in other countries such as Kenya where more than 10% of the households acquired improved stoves [40]. The reasons for this variation are not clear but could be linked to the interaction between technical issues and socio-economic imperatives.

In rural areas, open fires used for cooking also provide energy for space heating and lighting. Portable home-made metal containers, with holes on the sides are used as heating stoves. These are known as *mbaura* or *imbaula* in local dialects. Fuelwood or charcoal is burnt inside these stoves.

4.2. Co-generation and co-firing

Two major sugarcane estates are found in the Lowveld in the south-western parts of the country. These are Triangle Sugar Limited and Hippo Valley estates. The sugarcane estates produce about 5 million tones of residues per year with an energy value of 44.6 pJ [20]. This is a large amount of fuel that can be used to generate electricity for the grid [44]. Cogeneration is the sequential generation of thermal energy (steam) and electrical power [44]. This is mainly via electricity generation plants using steam turbine systems.

Cogeneration is practiced at the two sugar estates based on the bagasse produced from sugarcane crushing. Research was being undertaken in the country to try sweet sorghum as a replacement for sugarcane [29]. The bagasse is burnt as a disposal measure to generate electricity. The power plants at the two estates have a combined installed capacity of 81.5 MW electricity for their own use as well as feeding into the grid [45]. The power plants are based on low-pressure boilers (31 bar) and efficiencies for such systems are normally below 20% [45]. Modern biomass high-pressure (60–100 bar) boiler turbine systems produce electricity with efficiencies approaching 32% [45].

The potential for cogeneration in Zimbabwe's sugar industry has been examined [44]. The findings have indicated technological improvements that can be made to improve process and energy efficiency. These are based on comparisons with state-of the-art technology for bagasse energy cogeneration in Mauritius. The capacity at the two sugar estates can be increased to 210 MW by setting up two plants of 105 MW each, providing about 517 GWh of clean bagasse power [44]. The technological improvements that have been suggested are as follows [45]:

- electrification of all steam driven equipment,
- minimizing breakdowns through improved maintenance,
- installing more efficient juice heaters, evaporators and pans,
- optimizing equipment like electrical motors and training workers,
- increasing boiler capacity and upgrading boiler pressure,
- installation of an economizer to recover heat losses in the chimney, and
- upgrading of the steam turbines.

Sawmills in the eastern part of the country produce large amounts of sawmill residues which can be used for cogeneration. The only known use of the residues is combustion to fire boilers that produce steam which in turn is used to dry wood [29]. The Department of Energy through its National Biomass Strategy identified three potential projects for co-generation in the Eastern Highlands of Zimbabwe. The Nyanga Sawmill Wood Residue Project; which is situated at a Wattle Company site has been estimated to have generation capacity of about 3.5 MW. Chimanimani Sawmill Wood Residue Power Project situated at a Forestry Commission site has a capacity of 3 MW, and the Charter Sawmill Wood Residue Power Project situated at the Border Timbers site has a capacity of about 10 MW [46]. About 16.5 MW can be co-generated from these sites.

A modern practice which has allowed biomass feedstocks an early and cheap entry point into the energy market is the practice of co-firing a fossil fuel (usually coal) with a biomass feedstock [47]. Co-firing of coal and biomass in electricity generation is a technology that has been demonstrated, tested and proved in all boiler types commonly used by electricity utilities [48]. There is no commercial application of co-firing as an energy production technology in Zimbabwe. Given the availability of biomass resources and the known benefits of co-firing, it is only prudent that co-firing be part of the biomass energy technologies in Zimbabwe.

4.3. Carbonization

Carbonization is an age old pyrolytic process optimized for the production of charcoal. Zimbabwe is a low charcoal producing

country compared to other countries in southern Africa [20. In Zimbabwe charcoal production is limited to a few small-scale commercial schemes, all of which are directly associated with commercial forestry plantations. Three charcoal production operations were identified during the Energy Sector Management Assistance Program study of 2000 [49]. The largest is maintained by the Wattle Company Ltd., and this uses wattle residues. Total potential for charcoal production from the three main forestry companies in the country is estimated to be 41,200 t [50].

Little charcoal use occurs in Zimbabwe, and that which is produced is consumed by high-income urban dwellers [40]. The market for charcoal in Zimbabwe is limited. It is sold to richer households at supermarkets and gas stations [51].

Traditional methods are mainly used for charcoal production in the country. These are centered on the use of earth mounds or covered pits into which the wood is piled, burned and then covered with earth mounds. Control of the reaction conditions is often crude and relies heavily on experience. The conversion efficiency using these traditional techniques is very low. On a weight basis, estimates of wood to charcoal conversion rate for such techniques range from 6 to 12 t of wood per ton of charcoal [52]. Modern techniques of carbonization capture producer gas (CH_4, CO and H_2) which can be used as a fuel. In addition, some condensable vapors which form pyrolytic oils can be collected and used for the production of chemicals or as a fuel after cooling and scrubbing [53]. Other than carbonization, other pyrolytic technologies have no known application in Zimbabwe.

4.4. Gasification and liquefaction

Biomass gasification is a process that converts solid biomass such as fuelwood and agricultural waste to combustible gases with high conversion efficiency (~85%) [41]. The result is an inflammable mixture of gases known as producer gas, comprising CO, H_2, and CH_4 along with CO_2 and N_2 [41]. Producer gas has wide applications which include use in the Fischer–Tropsch processes.

Gasification and liquefaction of biomass is very limited in Zimbabwe although a lot of potential exists for gasification of forestry residues on several specific forestry plantations in the country [29]. There is no meaningful data in Zimbabwe on application of these technologies. Gasification as a technology would be feasible in areas such as forestry plantations where there would be a constant supply of raw materials. This technology has been successful in developing countries such as the Philippines and India where a number of exploratory activities were undertaken to introduce the technology as a fuelwood-saving measure in plantations and as a replacement for furnace oil used in boilers in small industries and in small power generating systems [41]. There is need for more work to be done in promoting this technology in Zimbabwe.

4.5. Densification

Compaction of biomass waste material to denser and easier to handle products has been known to increase heating value per unit volume making biomass more compatible with coal and more efficient in combustion [54]. Various studies have shown the benefits of biomass briquetting [54–56]. There are no known operational briquetting schemes in Zimbabwe. Two attempts have so far failed to take off the ground [29]. A project for a 26 kW plant using sawmill residue briquettes failed because the plant did not address the sawmill residue problems as it could only briquette 2% of the sawdust [29]. The briquettes produced also were found to have no local demand as they were not popular with the people.

The focus should therefore be to make a market research and come up with the appropriate technology for producing briquettes that are acceptable and meet the needs of both industry and the community.

4.6. Biomethanation

Bio-methanation has been practiced in Zimbabwe for some time now. Biogas has been produced in Zimbabwe at only 8% of the potential [23]. There are more than 400 bio-digesters installed in Zimbabwe with a capacity of between 3 m^3 and 16 m^3. At an average rate of gas production of 0.03 m^3 kg^{-1} of dung and at the daily feed rate of 25 kg m^{-3} [57], these units have the capacity to produce between 2.25 and 12 m^3 of biogas per day. The technical potential for biogas units in Zimbabwe is about 5000 m^3 [29]. The Ministry of Energy and Power Development has built biogas plants as demonstration projects at institutions, communities and exhibition centers around the country. Others are also in use on commercial farms and selected industries. The main feedstocks are cattle dung and pig manure. Biogas is also used for household chores such as cooking.

Energy poverty is rampant in rural areas in Zimbabwe. It has been postulated that a rural household with 2–5 cattle can have 20–25 kg of manure available to them and they can use this manure in 1–2 m^3 family size biogas plants fed at 20–25 kg m^{-3} rated capacity of the plant [58]. This will provide 0.6–1.5 m^3 of biogas per day for domestic consumption. The use of biogas will help in reducing the people's dependence on fuelwood and will also provide rich manure in the form of biogas plant digested slurry. This can contribute to sustaining agricultural production [59].

In addition to biogas generated from animal waste, Zimbabwe has several municipal plants that produce biogas from anaerobic waste digesters. All the major cities in Zimbabwe treat their sewage by anaerobic digestion [23]. Harare has five sewage treatment works. But only two (Firle and Crowborough) have biogas digesters. The bio-digesters at Harare's Crowborough and Firle works produce 8500 m^3 and 17,000 m^3 of gas respectively [60]. Some of the gas produced at the two plants is used for heating digested sludge which has to be maintained at a suitable temperature of 35–37 °C for the digestion process to proceed satisfactorily [29]. The rest of the gas is flared as waste gas [29]. The potential for methane production also exists in the city of Bulawayo as well as the smaller cities of Mutare, Gweru and Masvingo. The potential of biogas production from sewage treatment in four cities in Zimbabwe is shown in Fig. 2.

A lot of MSW (552,975 t) is produced in urban areas of Zimbabwe and is dumped in landfills. Currently there is no

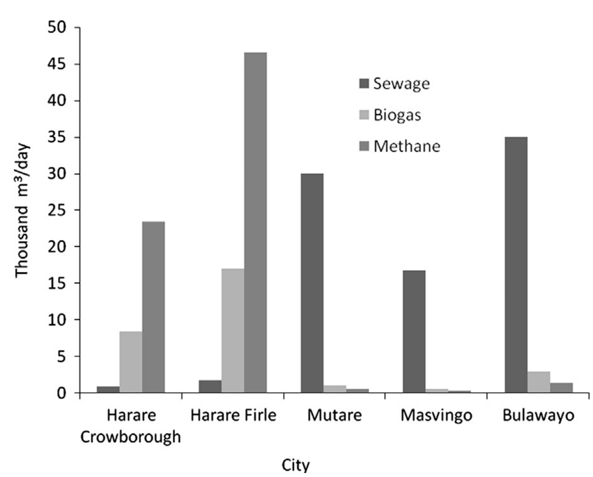

Fig. 2. Methane production (m^3 day^{-1}) from sewage plants using bio-digesters in Zimbabwe [29].

commercial use of landfills in Zimbabwe for energy purposes. It is known that the decomposition of biodegradable MSW in landfills produces methane. Elsewhere, this gas is mined and used as a source of energy. As of 2001, there were 955 landfills in the world that recovered biogas [61]. Methane is a greenhouse gas (GHG) that is 30 times more powerful than carbon dioxide in trapping heat in the atmosphere [62]. By trapping and utilizing the methane, GHG impacts are avoided. Biodegrable MSW can be into biogas by anaerobic digestion [23].

4.7. Bioethanol production

Ethanol is the most widely used liquid biofuel in the world [63]. Ethanol is a well known renewable green energy, mostly used to increase octane rating and improve emissions quality of gasoline. Ethanol has been used as an automotive fuel blended with gasoline to form gasohol.

Two large sugar mills in the southeast of Zimbabwe, Triangle Limited and Hippo Valley Estates produce about 80% of the country's sugarcane. Triangle limited is involved in ethanol production and the plant was designed to produce 120,000 l/day^{-1} giving an annual yield of 40 million liters of ethanol [47]. The ethanol plant was commissioned in 1980. Ethanol has been successfully produced from sugarcane in Zimbabwe with an energy output to input ratio of 1:1.9 [64]. It is also practicable for this ratio to be improved to between 3.8 and 4.1 [64]. Ethanol has been used in Zimbabwe to blend with gasoline. In the early 1980s, Zimbabwe actually achieved national blending levels of about 20% [46].

In 2008 the Zimbabwean government invited investors to invest in anhydrous ethanol production in the country. As a result, a large ethanol distillery plant was constructed at Chisumbanje and was completed in September 2011 [65]. The plant has an expected output of 100 million l per annum in the first phase. Projections were that the ethanol plant would later diversify into the generation of electricity, starting with production of 18.5 MW in 2011 and expanded to 36 MW in 2012 [65]. The plant includes milling, electricity generation, fermentation, distillation and dehydration of ethanol [65]. The ethanol plant in Zimbabwe is an example of a biomass-to-energy system which has operated successfully for almost two decades.

What is worth noting is that ethanol production in the country is solely from sugarcane. There is no production of ethanol from cellulosic materials or other starch-rich crops which are abundant in the country. Technologies do exist which can be used to exploit these materials for ethanol production.

Another product that has been made from ethanol is ethanol gel. Ethanol gel is a clean-burning fuel that consists of gelatinized ethanol bound in an organic pulp (cellulose) thickening agent and water. It is used as a substitute for kerosene in household activities such as cooking, lighting and space heating [29]. Cooking stoves specially designed for use with ethanol gel have been developed. Used in such appliances ethanol gel is a highly controllable, easily lit fuel with a heating efficiency of roughly 40% [66]. The calorific value of the gel fuel compares favorably with that of paraffin.

4.8. Biodiesel production

Esters of vegetable oils have been used as renewable alternatives to petroleum diesel. These esters are called biodiesel. Many studies have shown that the properties of biodiesel are very close to diesel fuel [67]. The esters can be blended up to 20% with petroleum diesel and can be used in all diesel engines. Higher blends of up to 100% are becoming possible with newer versions of engines.

In 1985 under the first five year national development plan, the government of Zimbabwe instituted a policy emphasizing liquid fuels research and development in an effort to conserve resources with a major bearing on foreign currency expenditure [3]. This led to research on the use of vegetable oils or their esters as diesel extenders. As a result, there were efforts to promote the production of *J. curcas* as the source of the oil for biodiesel production. However, there was no meaningful progress and no production and utilization of biodiesel was ever done in that 5 year period.

There were renewed interests on biodiesel production in 2005. The production of *Jatropha* as an energy crop gathered momentum in 2007. The government of Zimbabwe through the National Oil Company of Zimbabwe (NOCZIM) instituted the *Jatropha* growing project in March 2007 [65]. The project was aimed at intensive production of *Jatropha* plants with the ultimate objective of massive processing of biodiesel. The project was guided by the following specific objectives [3]:

- to produce biodiesel to meet 10% import substitution by 2017 (about $100dam^3$ per year);
- to produce 360,000 $t/year^{-1}$ of feedstock base (this yields about $100dam^3$ of biodiesel); and
- to establish about 1220 km^2 of *Jatropha* plantations.

The project targets willing smallholder farmers and large-scale farmers who have access to land and have capacity to produce *Jatropha*. The biodiesel project led to the establishment of a biodiesel refinery plant in Zimbabwe in 2007, the first of its kind in southern Africa. The plant has capacity to produce 35 dam^3 of biodiesel per year [65]. The plant started operating on cottonseed and soybean as feedstock due to the shortage of *Jatropha* seeds. However, in more recent times, the project is facing challenges due to shortage of feedstock [65]. This indicates the need to develop feedstock production systems as the basis of a sustainable biodiesel production value chain.

5. Techno-economics

Data on the current quantities of energy produced from the potential energy value of biomass materials are patchy in Zimbabwe. But what is clear is that exploitation of biomass for energy purposes needs to be enhanced. As shown in this paper, the technologies to support biofuel production exist. Without doubt, and with developments in conversion technologies, the costs of biofuels are likely to be favorable in the long run.

Biofuels would be a viable alternative if their costs are less than those of fossil fuels. Appropriate data for economic comparison of various fuels are not adequately available in Zimbabwe. Using gasification as an example, Dasapa [68] showed that on average in SSA, the cost of electricity from a biomass gasifier is $0.183 kWh compared to $0.50 kWh for diesel-based generation. In 2013 1 l of gasoline blended with 10% ethanol (E10) cost $1.44 compared to $1.57 for a liter of gasoline in Zimbabwe. This 9% price differential could indicate cost benefits of ethanol as a fuel. Much still needs to be done to ascertain the economic dynamics of biofuels in Zimbabwe.

6. Conclusions

Bioethanol, biodiesel, biogas, biomethanol and biohydrogen remain the five leading biofuels in use worldwide. Whereas the preponderance in Zimbabwe is use of solid biofuels, mainly fuelwood, with little use of liquid and gaseous biofuels. Direct combustion remains the major technology for conversion of biomass into energy. Production

of liquid fuels by transesterification and fermentation was gathering momentum in the country. These two technologies provide the greatest opportunities for production of biofuels in Zimbabwe. On the other hand, technologies such as co-generation, co-firing, carbonization, gasification and liquefaction are not fully exploited. There is need for optimum use of these technologies in order to broaden the array on energy production options from biomass. It is without doubt that Zimbabwe has the potential to generate 409 pJ from biomass. Thus, the need to optimally utilize the biomass resources for energy production cannot be overemphasized.

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